**Published version of this paper:**

- **http://www.sciencedirect.com/science/article/pii/S2213305415300035**
- doi:10.1016/j.ancene.2015.05.004
- Aks a copy by email: bastiaan.notebaert@gmail.com

# Quantifying the anthropogenic forcing on soil erosion during the Iron Age and Roman Period in southeastern France

**Bastiaan Notebaert**

*Universiteit Gent, Krijgslaan 281 S8, 9000 Gent, Belgium*

*Leuven University (KU Leuven), Celestijnenlaan 200E , 3001 Leuven, Belgium*

**Jean-François Berger**

*Université de Lyon, UMR 5600 EVS/IRG-Lyon 2, France*

## ABSTRACT

This study combines a traditional qualitative description of sedimentary units with a quantitative sediment budget approach to document the colluvial and alluvial sediment dynamics in the Valdaine region (Drôme, France) from the Iron Age to the early medieval period (700 BC – 900 AD). Three transects through colluvial and alluvial deposits are discussed in detail to demonstrate the way in which absolute dating techniques and archaeological evidence are combined to establish a stratigraphic framework. This framework is applied to 16 sites and further combined with an existing sediment budget to quantitatively reconstruct the catchment-wide sedimentary evolution. Results show large variations over time in sediment deposition: a first phase from 700 to 400/300 BC, followed by an incision phase between 300/200 BC and 100/50 BC, an unprecedented peak in

deposition during the Roman period (100/50 BC-450 AD), with continued but decreased deposition from 450 to 900 AD. These results show how sediment deposition relates to increased population density and anthropogenic land use on a timescale of a few centuries. The analysis indicates important erosion and deposition phases during the Roman period, considered to be a warmer period (*Roman warm period*). A relation to particular regional climate variations could not be discovered, possibly because of the temporal resolution of the sedimentological data that still fail to identify events lasting a few decades to a century.

# I. INTRODUCTION

Soil erosion and sediment redistribution are processes with important potential consequences for human societies (e.g., Dotterweich, 2008). As agents of erosion, humans have become an integral part of the earth system, but all past processes and environmental effects are not understood. A full understanding of these interactions between the earth system and humans during the Holocene can only be achieved through detailed reconstructions of climate, human activities and earth system processes, and their interactions in the long-term (Dearing, 2006). Different studies have shown how sediment deposition has varied in the past as a result of anthropogenic activities and/or climatological events (Dotterweich, 2008; Notebaert and Verstraeten, 2010; Dusar et al., 2011). Most studies focus on single-site sedimentation rates and site-specific connections between environmental drivers and erosion (e.g., Arnaud et al., 2012; Doyen et al., 2013; Simonneau et al., 2013), but over the past decades studies have increasingly focused on spatial patterns and quantification of sedimentation on a catchment scale (Trimble, 1999; e.g., Verstraeten et al., 2009a; Notebaert and Verstraeten, 2010). One of the applied techniques is the construction of sediment budgets. A sediment budget includes the sources and sinks of sediment for a given spatial unit over a given time period (Slaymaker, 2003; Reid and Dunne, 2005). Sediment budget covering periods of important variations in human land use have mainly focused on North America (e.g. Trimble, 2009) and Central and Western Europe (e.g., Notebaert et al., 2009; Fuchs et al., 2011; Houben, 2012). These budgets range from quantifications of sediment masses for one type of sediment sink, typically floodplains (e.g., Stolz et al., 2012), to time-differentiated budgets containing different sinks and/or sources (e.g., Trimble, 2009; Notebaert et al., 2011a; Fuchs et al., 2011). The temporal resolution of such sediment budgets is however strongly limited by the availability in time and space of detailed chronologies. Only for a few European studies is detailed (centennial scale) chronological information available (e.g., Trimble, 2009; Fuchs et al., 2011).

Sediment budget studies have contributed to the understanding of processes that occurred during the transition to an Anthropocene or human-dominated environment (e.g. Trimble, 1999). They have shown how different parts of the landscape react with a different intensity, and at different moments in time, to major disturbances (e.g., Trimble, 2009; Notebaert et al., 2011a). Because of methodological constraints related to the longer timescales involved the resolution for sediment budgets in Europe is typically less defined than in North America. A detailed relationship between the first intense land use and its geomorphologic impact is not detected, although the sediment budgets provide information covering a period of centuries to millennia. Therefore this study attempts to contribute to the understanding of processes that occurred at the point of transition towards a human-dominated environment, to provide a detailed temporal scale so that the sedimentary processes can be more directly linked to the anthropogenic changes in the landscape.

The objective of this study is to quantify the variation in sediment deposition for the Valdaine region (southeastern France) from the Iron Age to the early medieval period (ca. 700 BC – 900 AD). During this period human impact peaked (for the first time) in this region, transforming it into a human-dominated landscape. We will test how sediment budget techniques can be used to derive region-wide temporal variations in sediment deposition, and whether these can be linked to environmental changes. We will do this by combining detailed site-specific geomorphological reconstructions with a quantitative analysis on a regional scale.

## II. STUDY AREA

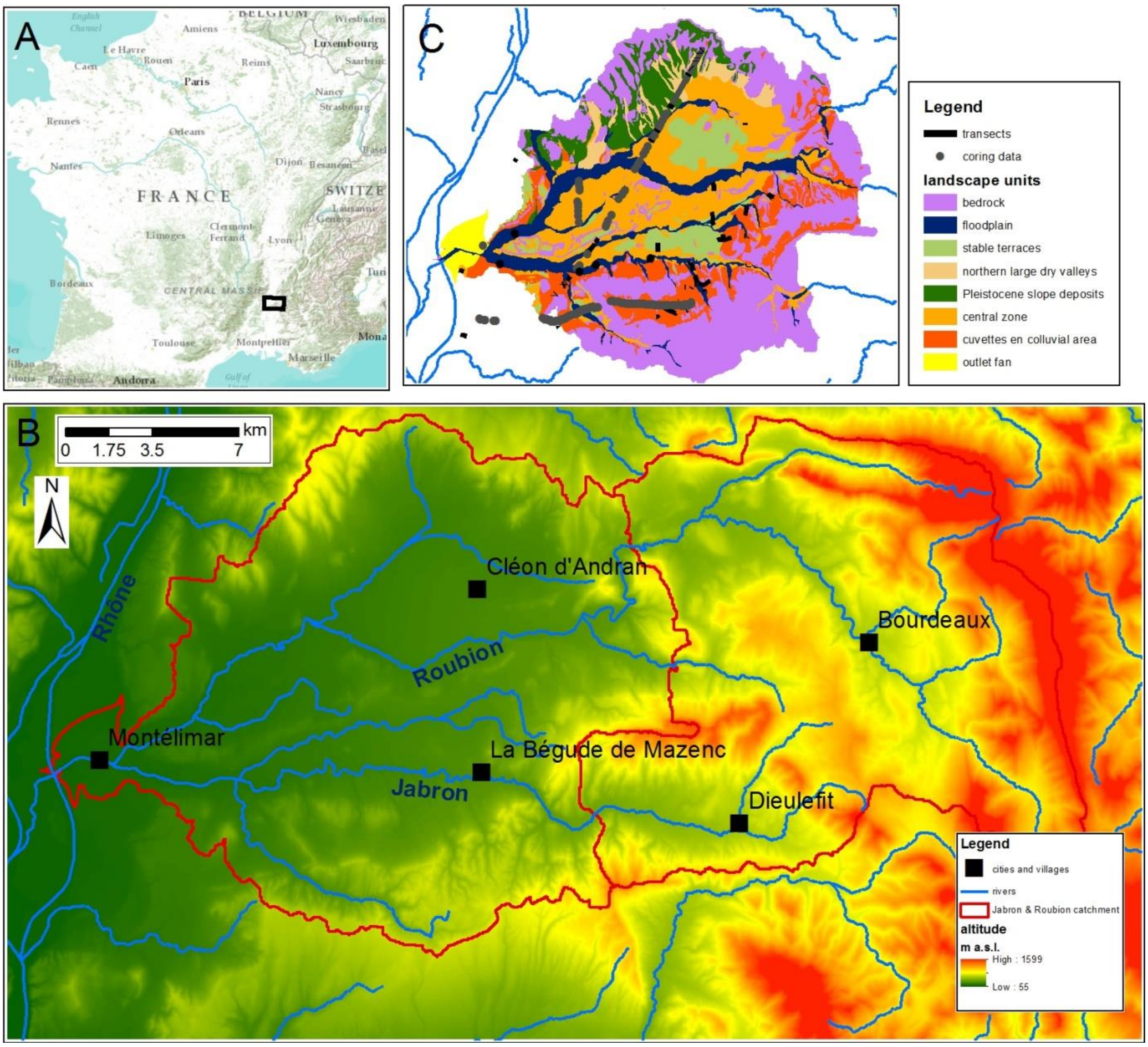



**Fig. 1: Study area (334 km²). A) Location of the study area (black square indicates location of map B) in France (background: World Topographic Map, ESRI). B) overview of the study area: topography, hydrology and main towns. The red polygons indicate the Roubion and Jabron catchments, of which only the lower part (western polygon) is the Valdaine. C) map of the main geomorphic regions in the Valdaine region and data used to construct the sediment budgets. The geomorphological regions are based on (Notebaert et al., 2014) to construct the sediment budget.**

This study focuses on the Valdaine region (334 km²; fig. 1), located in the Rhône basin. The Valdaine region is the lower part of the Roubion and Jabron River catchments (total 610 km², of which 276 km² are upstream of the Valdaine), which have their upper tributaries in the calcareous Pre-Alps. The Jabron flows into the Roubion at the city of Montélimar, located at the western edge of the Valdaine, just before the Roubion flows into the Rhône. This study focuses on the Valdaine rather than on the entire Roubion and Jabron catchments, because of the major differences in geomorphic system, land use history, and data availability.

The topography of the Valdaine (fig. 1 B) is determined by the geological structures. The outer fringes of the Valdaine are pre-mountain ridges with steep topography: the steeper and topographically highest parts are limestone ridges, while lower and less steep parts are composed of a marl lithology. The lower slopes of these ridges are covered by Pleistocene footslope deposits. The altitudes of the top of these ridges range in general from 500 to 600 m a.s.l., with a maximum of 850 m a.s.l. for the eastern ridges. The slope angles often exceed 10%. The central part of the Valdaine is a structural depression in mostly soft marl deposits, with an altitude of 70 to 200 m a.s.l. This central part has a gently rolling topography, and there are also some extended flat river terraces. These terraces are dominated by slightly weathered gravel deposits and have calcic to leached red/brown Mediterranean soils (chromic Luvisol), while the rolling hills have often a brown to calcareous Pleistocene colluvial soil cover. The Holocene floodplains of the Roubion and the Jabron broaden downstream. A large alluvial fan is formed at the catchment outlet, just downstream from the Jabron-Roubion confluence, with a recent fluvisol cover, and the city of Montélimar is located on this fan. Slope angles rarely exceed 2 % in this central part, but some calcareous hills also protrude in this central plain, with slopes >10% and height differences of more than 50 m.

The climate of the region is transitional between Mediterranean, continental and Atlantic climates (Blanchet, 1990) with a total average annual precipitation of 900 mm-1000 mm

(Hirsch and Vincent, 1966; Blanchet, 1990). There is a high inter-annual variability in the precipitation pattern (300-1700 mm interannual variation), some years having heavy precipitation in spring and in fall (September to November), typical for a Mediterranean climate, while in other years precipitation occurs more evenly over the year.

The archaeological records of the Valdaine region are quite extensive, with most information originating from field walking surveys and rescue archeology projects (such as *Archaeomedes* (1990-1998), ATP CNRS (1986-1989, 1990-1994), TGV-Méditerranée (1995-1997)). Settlement density reconstruction shows an intensive occupation history from the Neolithic period onward (Berger, 1996; Berger et al., 2007b; Berger, 2011). It peaks for the first time during the middle Neolithic period (ca 4500 – 3500 BC) (Berger, 1996), then this period is followed by a phase of land abandonment with forest regeneration during the Early to Middle Bronze Age (ca 2300 BC – 1400 BC). This is followed by a gradual opening of the environment during the latter part of the Bronze Age that culminated at the end of this cultural phase ('BFIIIb period', 900-750 BC) (Berger et al., 2007a). In the Iron Age (750-50 BC) there was a more open and humid landscape, according to malacological data (Berger et al., 2000). After a short period of land abandonment around the transition from the Bronze Age to the Iron Age (ca 750 BC), the end of Iron Age Period 1 (IAP1, 750-600 BC) shows a new increase in settlements, lasting until the first part of Iron Age Period 2 (IAP2, 600-300 BC). A new short period of land abandonment is observed during the middle of the IAP2 (300-200/160 BC), followed by a final peak at the end of IAP2 (200/160-50 BC) indicating unprecedented growth during the Roman period (Berger et al., 2007b). A major peak in settlement density occurs during the first part of the High Roman Empire (ca 1-150 AD). This is followed by a relative decrease in settlement density during the Low Roman Empire (ca 200-500 AD), and especially during the early and high Middle Ages (from ca 500 AD on). This is again followed by peaking settlement densities from 1000 AD onward (Berger, 1996).

These societal tendencies are common in most areas of southern France and represent the historical dynamics of man-environment interactions at a regional scale (van der Leeuw and Team, 2005).

## III. METHODS

In this paper we present three transects through representative sites for alluvial and colluvial deposition in the Valdaine: transects Charols-Grand Bois (A; colluvial), La Bégude-de-Mazenc/T37 (B; alluvial) and Montélimar-Beaulieu (C; alluvial). These transects are based on trenches and transect Montélimar-Beaulieu is complemented with data from cores to map the deeper sediments. These transects were first studied within the framework of geo-archaeological projects, and are as such previously published in local (non peer-reviewed) literature and archaeological reports (Berger, 2003; Thiercelin-Ferber, 2012), although figures have been modified for this paper in order to better represent the temporal tendencies and the rise of floodplain storage in the late Holocene period. Trenches and cores are studied using a standard methodology which provides a detailed description of the fluvial geomorphology using color, texture and other sedimentary and pedological properties (such as inclusions, concretions, weathering/depletions features …) of the different sediment units with a vertical precision of ca. 5 cm. Dating of deposits is based on AMS radiocarbon dating of charcoal, wood and in the best case, terrestrial burnt seeds. In many cases charcoal beds or lenses, which reflect past fire activity, have been used. The dates from the older literature were obtained by the standard method. The radiocarbon database comes from palaeosoils, alluvial and colluvial formations. We try to avoid "old wood effects" in the last years by systematic charcoal identification of pedosedimentary formations (see Delhon and Thiebault (2008)). In addition archaeological information is used to date sedimentary units: the presence of material (mainly pottery sherds), especially when abundant and dated to a single period, and the presence of clear contexts (floors, roads, ditches, fireplaces). The possibility of reworking and re-deposition must be taken into account when using such archaeological data for dating, but in this study they are cross-dated with radiocarbon dates (see also Berger (2015)).

The data from these three field sites combined with existing data are used to construct a time-differentiated sediment budget. The existing data (table 1) on deposits are detailed descriptions of trenches (a few meters long to more than one km) along hillslopes, through dry colluvial valleys and in floodplains, and large coring datasets along coring transects. These data are complemented by new data from cores obtained in the OHM Valdaine project (2012-2013). Most of these existing data were originally studied by the second author of this contribution (unpublished work and e.g., Berger, 1996; Berger and Jung, 1999; Berger, 2015), and several detailed trench descriptions from other sources are used.

Constructing the time-differentiated sediment budget requires a quantification of Holocene sediment deposition and a time differentiation of these deposits. We used the same quantification we carried out for Notebaert et al. (2014). For each site (a site is a coring transect and/or a trench) we calculated the average sediment thickness. Next, landscape units were mapped based on Quaternary geomorphology and topography (fig. 1C, based on Notebaert et al. (2014)), and based on the site data we calculated the average sediment thickness for each of these units. The catchment-wide surface area of each landscape unit is then combined with these average sediment thickness values to obtain the total catchment-wide sediment deposition. This assumes that the sites provide a representative sample of those units. As sites are not concentrated in erosion or deposition zones (but randomly located) and data from cores are organized in a systematic way along linear structures (road, railroad or waterline constructions), we argue that they do provide a representative sample. When quantifying colluvial sediment we took into account the Valdaine region (334 km$^2$), mainly because of data availability and because colluvial processes can be assumed to be different in the upstream mountainous region. But for the quantification of alluvial sediments we also took into account these upper reaches (totaling 610 km²) as alluvial processes in the lower reaches (Valdaine) cannot be studied independently from the processes in the upper reaches.

For the time differentiation of the sediment budget we first quantified the number of sites over time for different types of geomorphic processes, and then calculated the quantities of sediment deposited for each time period. For 20 colluvial sites of the previously mentioned database (see table 1 for sources) we could assess the active geomorphic process for each 50-year time period between 700 BC and 900 AD. Sites are included only when the beginning or end of a specific geomorphic process could be dated within 100 years, or better, in the original publication based on archaeological data and/or radiocarbon dating. The factors considered are sediment deposition, stability (neither deposition nor incision), incision of previously deposited sediments, or the absence of data. The period of stability and/or incision phases is considered to be the entire period between the deposition of the pre-dated and the post-dated sedimentary layers. A comparable figure could not be constructed for alluvial deposits, as only for a limited number of sites (n=3) could the processes be identified with a sufficient temporal resolution.

Next we quantified sediment deposition during the concerned timeframe (700 BC – 900 AD) for the 16 sites for which such quantification was possible. Quantifying sediment deposition is only possible when sediment bodies can be well discriminated and average sediment thickness can be calculated for a specific time period. For each site average sediment deposition (thickness) or incision is calculated for different timeframes, the latter based on the ages for the beginning and end of the deposition of distinguishable sediment units, or inferred stability/incision periods between deposition of these units. This means that the timeframes for which sedimentation rates are calculated are site-specific. These values are compared to the total Holocene sediments present today, in order to calculate relative sedimentation volumes ($S_r$; % of total Holocene deposits; $S_{r,i}$: $S_r$ for period i):

$S_{r,\,i}=V_i/V_{Hol}*100$

with $V_i$ being the area-specific volume of sediment deposited during time period i ($m^3/m^2$) and $V_{Hol}$ being the total area-specific volume of the Holocene sediment present today ($m^3/m^2$). Typically $V_i$ and $V_{Hol}$ are average sediment thicknesses for the site. Values of $V_i$ can be negative when incision occurred during time period i, indicating the average incision depth.

In order to enable a comparison of sedimentation volumes ($S_r$) for time periods with different lengths, relative sedimentation rates are calculated ($SR_r$; $SR_{r,i}$: $SR_r$ for period i expressed in % per 1000 years):

$SR_{r,i} = S_{r,i}/T_i *1000$, with Ti the duration (in years) for period i.

Combining sedimentation rates with the sediment deposition quantification results in a time-differentiated sediment budget. In order to obtain a catchment-wide overview of sedimentation rates, average values of $SR_{r,i}$ are calculated for each 50-year time period based on these site-specific rates. A 50-year period is chosen as this equals the temporal resolution of cultural periods (See *Archaeomedes* project, van der Leeuw et al. (2003)). A more detailed resolution is not feasible because of the resolution of the dating methods used, while a coarser resolution would result in data loss.

When comparing quantities with those mentioned in the literature, we converted volumes to mass by using a bulk density of 1.5 $10^3$ kg $m^{-3}$, comparable with other studies (e.g., Hoffmann et al., 2007; Notebaert et al., 2014). In order to take into account scaling effects between catchments, values for sediment mass are converted to area-specific values by dividing through the catchment area.

| No | Reference | Type | Data |
|---|---|---|---|
| 1 | Berger (1996) | PhD | Ca 65 profiles based on trenches, 4 cores, 24 deep cores |
| 2 | Berger (2011) | Paper | 10 profiles |
| 3 | Berger and Guilaine (2009) | Paper | 9 profiles |
| 4 | Berger and Jung (1999) | Archaeological report | 3 profiles (including several cores) |
| 5 | Berger et al. (2000) | Paper | 1 profile |
| *6* | *Berger, pers. comm.* | *Unpublished data* | *(originals of sources 1, 4)* |
| *7* | *Brochier, pers. comm..* | *Unpublished data* | *67 cores, 18 profiles (including source 10)* |
| 8 | Brochier and Berger (in prep.) | Personal archive/publication in preparation | (based on sources 1, 4, 6, 7) |
| 9 | Ronco et al. (2008) | Archaeological report | 110 cores |

| | | | |
|---|---|---|---|
| 10 | Thiercelin-Ferber (2012) | Archaeological report | 1 profile |
| 11 | Verhagen and Berger (2007) | Paper | |
| 12 | Vital et al. (1999) | Paper | 1 transect |
| 13 | Notebaert et al. (2014) | Paper | 20 cores |
| 14 | This Study | | 3 profiles |

**Table 1: Sources used for the sediment budget and time differentiation. Note that some data are repeated in different sources.**

## IV. **RESULTS**

### Typical colluvial and alluvial cross sections

The three long Holocene sequences discussed in this paragraph (2 fluvial and 1 colluvial) represent a summary of the Valdain Basin database used to build the quantitative budget. We have chosen a temporal alluvial and colluvial visual presentation of the data rather than a classic lithic and pedostratigraphical reconstruction, to accentuate graphically the acceleration of sedimentation in both sedimentary contexts from the Iron Age period (750 BC). The transect Charols-Grand Bois (fig. 2A) is located on the hill slopes of a marl-sandstone hill, in the SE of the Valdaine. A black washed-out palaeosoil is located in the western palaeo-depression of the transect, the result of a long stability phase during the early Holocene (Ia on fig. 2A). This stability phase is followed by the deposition of two colluvial layers (Ib-c): the first is decarbonated, the second one contains calcium carbonates. The next deposit is a thick red-brown sandy loam with reworked sherds from the late Bronze Age (IIIa). This layer fills most of the two early Holocene palaeo-depressions of the profile, during a phase of increased runoff, and can be dated to the first millennium BC. There was an incision phase before the Roman period that removed a part of the older deposits and created new depressions. These erosion forms are filled with brown-yellow sandy colluvial material with spread gravels (IIIb). They contain numerous Roman remains from the early period of the empire, and a ditch from the same period. A medieval palaeosol (IV) has formed on top of this Roman layer. It is covered by thick colluvial deposits, dating to the medieval as well as more recent periods (V), indicated by the sherds from the 11th-12th centuries in the colluvial material just above it.

The second profile (La Bégude-de-Mazenc/T37; fig. 2B) shows the alluvial sequence of the Bramefaim River, a tributary of the Jabron located on the Quaternary river terraces of the central Valdaine. Different phases of Holocene alluvial activity are present within the floodplain which has a width of ca 300 m and a sediment thickness of 2 to 4 m. Early Holocene deposits (I) are badly preserved due to later torrential phases and related incision. A palaeosol (II) is located on top of them. During the Iron Age the river broadened its floodplain and developed a braided pattern as a result of an increase in the river's energy (IIIa). During the Roman period an incised system formed with bedded deposits of sand and gravel (IIIb), and overbank deposits in the floodplain. After the Roman period the river bed became displaced during a new river incision phase, which corresponded to the development of a grey-brown alluvial soil (IV). After the 14$^{th}$ century three nested alluvial deposits (V) were formed, corresponding to a rapid aggradation of the river bed. Two to three meters of coarse deposits were deposited during the last 5 or 6 centuries, before the recent and current incision.

The third transect is the alluvial sequence of Montélimar-Beaulieu (fig. 2C), crossing the Jabron floodplain. Archaeological data and radiocarbon dating indicate that different aggradation phases are separated by phases of relative stability. The top of phase I (fig. 2C) represents the end of the aggradation of fine sediments (silt) at the end of the Neolithic period. Two deeper cores (not represented in the figure) show that these fine early Holocene deposits are slightly less than a meter thick (corresponding to a deposition rate of ca 0,12mm/year). A second deposition phase (II) corresponds to a slow aggradation combined with alluvial brown soil formation between ca 2000 and 800 BC (deposition of ca. 0,46mm/year). A first major peak in sedimentation occurs during the first part of the Iron Age (III), between ca. 800 and 200 BC, with a deposition rate of ca. 1.1 mm/year. This is followed by a short incision phase during the 3$^{rd}$ and 2$^{nd}$ centuries BC. A major sedimentation phase occurs from ca. 150/100 BC to the 3$^{rd}$ century AD, with a rate of ca. 2 mm/year. Deposition of local colluvial material along the floodplain edges demonstrates that the floodplain was well connected to the hillslopes at this location, probably due to the eradication of the floodplain forests (Berger, 2015). The first part of the medieval period shows a decrease in sediment deposition, and an important incision phase of the river in its older deposits. A final aggradation phase is associated with a torrential channel (Vb) which became aggraded from the 12-13$^{th}$ centuries AD onward to form a braided river channel during the 17-19$^{th}$ centuries AD. This corresponds to the regional trend towards formation of braided rivers during this period (Berger, 2015). Two floodplain deposits were formed: first (Va) yellow silt between the 12$^{th}$ and 14$^{th}$ centuries AD, followed by silt and sand (Vc) after the 14$^{th}$ century AD. Average sedimentation rates since the 12$^{th}$ century AD are about 1,43cm/year.

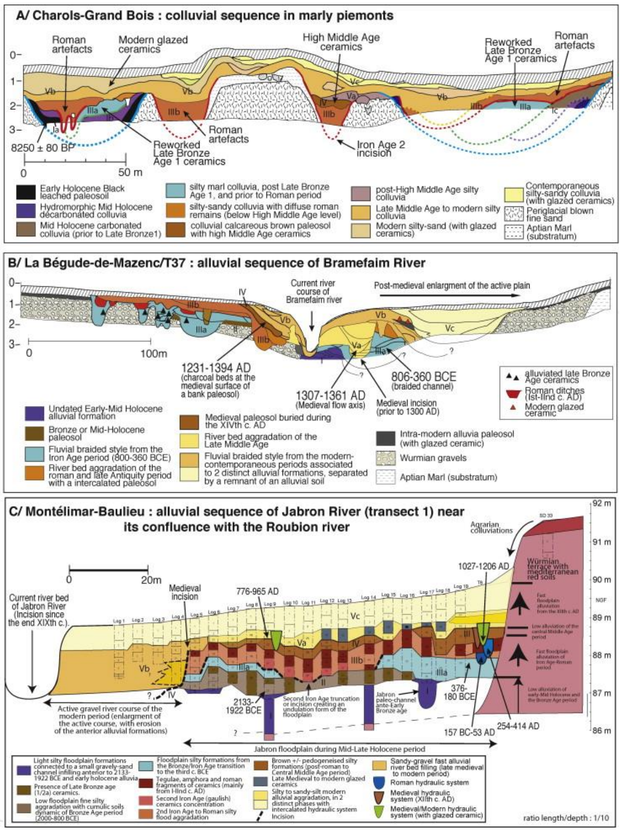


**Fig. 2: Examples of typical transects across colluvial deposits on a marly slope (A), a tributary floodplain (B) and the main Jabron River floodplain (C), illustrating the Holocene sedimentary evolution of the Valdaine basin. For the different transects, it is indicated how radiocarbon ages and a chronology based on archaeological artifacts combine to provide a more detailed image of Iron Age and Roman period deposition. Modified after Berger (2003) and Thiercelin-Ferber (2012).**

## Quantifying the sedimentation rates on a regional scale

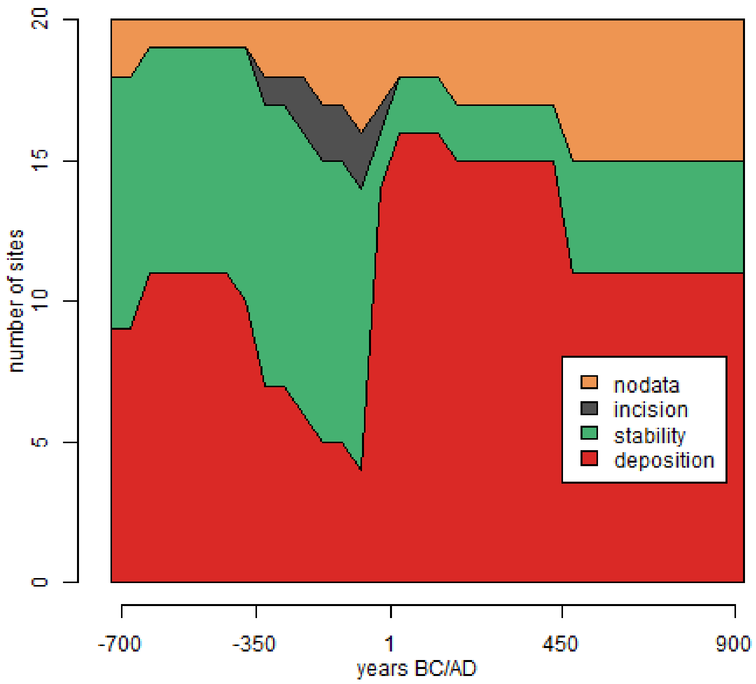



**Fig. 3A**

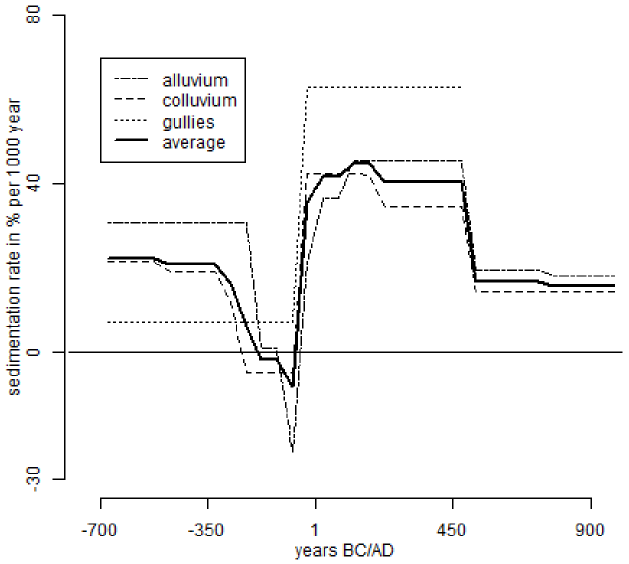


**Fig. 3B**

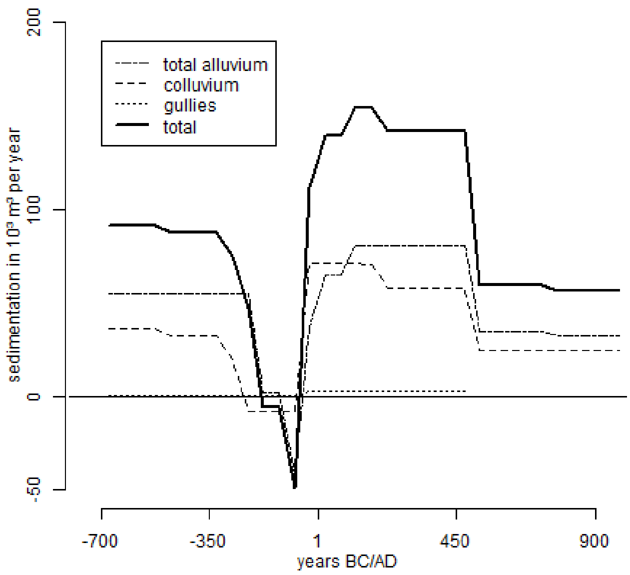



**Fig. 3C**

**Fig. 3: Temporal evolution of geomorphic processes between 700 BC and 900 AD. A) number of colluvial sites (n=20) with *incision*, *stability*, *deposition* or *no data available* per time slice of 50 years. B) relative sedimentation rates (in % per $10^3$ year) for alluvial sites (n varies between 3 and 6), colluvial sites (n varies between 5 and 9), mountain gullies (n varies between 0 and 2), and an average value for all sites (n varies between 8 and 16). C) evolution of total sediment deposition (in $10^3$ $m^3$ per year) for alluvial sites (entire Roubion and Jabron catchments, 610 $km^2$), colluvial sites (Valdaine, 334 $km^2$), mountain gullies (Valdaine, 334 $km^2$), and the sum of these sinks ('total'). This sum does not include possible mountain ravine and colluvial deposition in the upper mountainous parts of the Roubion and Jabron catchment.**

The temporal variation of the number of sites with active sedimentation (Fig. 3A) shows a major peak for the Roman period (ca. 1-400 AD), with secondary peaks during the late

Roman period and early medieval period (ca. 400/450-900 AD) and the first part of the Iron Age (ca. 700-400 BC). During the late Iron Age (ca. 350/200-50 BC) the number of sites with stability and incision dominate. This pattern provides a semi-quantitative image of the temporal variation in sediment deposition and shows the spatial expanse of the processes over time, but still ignores possible variations in sedimentation rates between the periods.

Also, the evolution of relative sedimentation rates (SR, fig. 3B) shows the highest values for all sediment sink types during the Roman period (ca 50 BC/1AD – 400/450 AD), with the lowest values (negative values indicating an incision phase) just preceding the Roman period (roughly 250 to 100/75 BC).

## V. DISCUSSION

### V.1 METHODOLOGICAL CONSTRAINTS

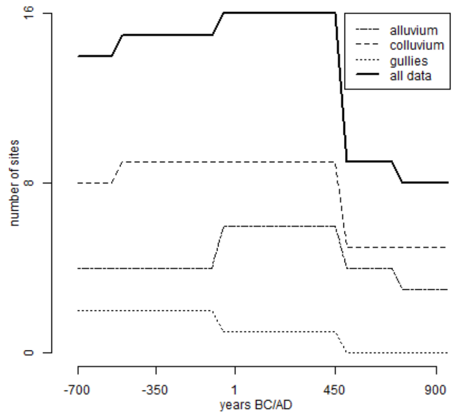
Quantification of sediment deposition for the sediment budget relies on the assumption that available data are representative for the landscape units used for the extrapolation. Although we did not assess error in the quantifications for this study, previous studies have shown that the margin of error in assessing sediment budgets using a comparable or smaller amount of data is around 10-20% (Notebaert et al., 2010).

Through the quantification of sediment amounts for different time periods, sediment budgets enable an objective comparison of variations over these periods. However, a major disadvantage is that their temporal resolution depends upon the availability of spatially distributed well-dated sites. As a result they provide a simplified image of past variations in sediment quantities and pathways, and variations which occur over relatively short timescales are not incorporated. In this study we attempted to identify variation in sedimentation within such shorter timeframes. This is possible due to the alternation of different geopedological processes (deposition, incision, stability) resulting in many recognizable discrete sediment bodies, and the abundance of archaeological remains that can be used for dating in combination with radiocarbon dates. Still, our calculation of sedimentation rates for each 50-year period (fig. 3B) depends on data with a much lower temporal resolution, as those discrete sediment bodies are typically formed during a period of 300 to 500 years, and site-specific rates are thus integrated over these longer periods. But the temporal precision of the dating of the beginning and end of the deposition of individual sediment bodies is 50 to 100 years for the sites examined, which justifies such a temporal resolution in this study. Thus, although the rates of deposition are averaged out over longer timescales than 50 years, the major changes in processes (deposition, stability, incision) are known at this scale. Calculated relative sedimentation rates ($SR_{r,i}$) for the different sites are based on published dated sites, and the original studies typically place distinct sediment units within a cultural period, rather than using absolute dates. These cultural periods have durations of a few centuries. Although we have no data for a more detailed temporal resolution, we assume that within these longer periods there will be additional variation in $SR_r$, and the $SR_r$ values used in this study are averaged values for these periods.

The problem of averaging sedimentation rates ($SR_r$) over longer time periods is encountered in many sediment budget (and other) studies and depends on the time differences between quantifiable points with known age. Only when a very detailed chronology can be established (e.g., Fuchs et al., 2011) will averaging effects be minimal.

Our calculation of $SR_r$ will thus be influenced by the cultural periods which define the dating resolution of each individual site. Therefore, we suggest that a quantitative interpretation should mainly focus on the timescale of these different cultural phases (typically 200-500 years), while the major changes in geomorphic processes (coinciding with the beginning and end of the formation of individual sediment bodies) alone can be interpreted at a resolution of 50 years.

V.2 SPATIAL AND TEMPORAL PATTERN



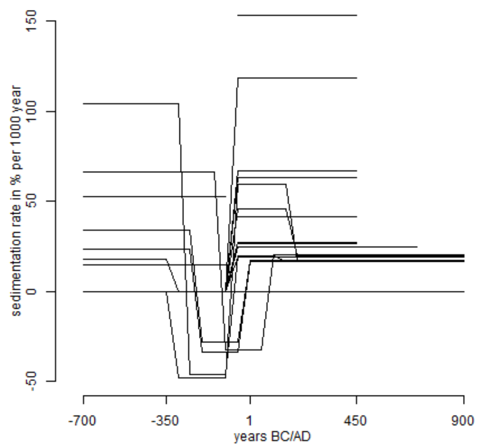




**Fig. 4: temporal variation in the number of sites for which site-specific rates are calculated, and temporal variation in site-specific rates for these sites. A) number of sites for which quantifiable data with a detailed chronology is available. B) site-specific SR (in % per $10^3$ year) for these sites.**

Average deposition amounts and $SR_r$ are calculated for each sediment sink type (colluvial, alluvial, mountain gullies). This gives us the catchment-wide pattern in the sedimentation history, but information on (spatial) variation within each sediment sink type is lost. When more data is available, the different studied sites could be separated into more types (e.g. discriminating between different types of colluvial deposits), although the number of sites examined has an important influence on the efficiency of the calculation of the averages. Even with our dataset the calculations for mountain gullies and alluvial sinks is hampered by the limited number of observations (fig. 4A).

The number of data available over time (fig. 4A) might also influence the calculated rates. There are clearly less data available for the period after ca. 400 AD, and in particular some sites with high $SR_r$ values in the previous period have no data for periods after 400 AD (fig. 4B). As a result, the calculated average $SR_r$ value for this post-400 AD period decreases partially due to lower data availability. Also, in previous studies such a temporal difference was observed in the quality and quantity of the data and rates were calculated according to an uneven chronological resolution of the ceramic markers (e.g., Berger et al., 2003). When individual sites are considered, it becomes apparent that the absence of information and calculated rates for the period after 400 AD is often the result of a low sediment rate (or stability and absence of sedimentation) and the resulting problem is identifying and quantifying sediment in an accurate way. For different sites, lack of data is also the result of an uncertainty in the dating of the beginning of the subsequent sedimentation or incision phase after 400 to 800 AD, which is often only dated as 'post-Roman' in the publications consulted. For well-dated sites in the larger region, a decrease in sedimentation rates often occurs after 600/700 AD (Berger and Brochier, 2006). Thus, this data decrease after 400 AD demonstrates a data bias in sediment budgets, with more data and a finer resolution for periods of increased sedimentation.

Our results (fig. 3B) show that colluvial and alluvial sedimentation follow more or less the same temporal pattern. A time lag can be observed during the late Iron Age in relation to the decrease in alluvial sedimentation and the change towards incision compared to colluvial sedimentation.

Such a time lag is also reported for other regions (e.g., Hoffmann et al., 2007; Trimble, 2009; Verstraeten et al., 2009b), where colluvial deposition has reacted more directly to changes in soil erosion rather than alluvial deposition. This may be due to a better connectivity between hillslope erosion and colluvial deposition (e.g., Notebaert et al., 2011b), and/or a latency in the diffusion process across the river watershed due to a complex system response (e.g., Trimble, 2009). This can be a result of the resilience and time required for adaptation of the active channel to a changing balance in water and sediment discharge (e.g., Lane, 1955; Trimble, 2010).

## V.4 SEDIMENT QUANTITIES

Combining the sedimentation rates with quantification results yields the temporal evolution of deposited sediment quantities for the Valdaine (in $10^3$ $m^3$ per year**,** fig. 3C). For this figure we used total colluvial deposition in the Valdaine region (334 $km^2$), and total alluvial deposition in the entire Jabron and Roubion upper catchment area (610 $km^2$). These data show that the mountain gullies have a very limited contribution to sediment deposition. Total sediment deposition peaks around 100-150 AD, while there is a peak in net sediment removal from existing deposits (incision) around 100-50 BC. Total colluvial deposition in the Valdaine between 700 BC and 900 AD (a period of 1600 years) equals ca. 60.1 $10^6$ $m^3$. Although sedimentation peaks in the Roman period (ca. 150 $10^3$ $m^3$ per year), it is still considerably lower than sedimentation during the last 1000 years (ca. 300 $10^3$ m3 per year based on fig. 6a in Notebaert et al. (2014)).

Results can be compared with values reported for other catchments (see table 2), although only a few studies report values for a period shorter than a couple of thousand years. For this table we have selected available quantifications for periods coinciding with the first reported widespread anthropogenic impact on the landscape. The coarse temporal resolution of many studies has an important influence on their results. For instance, in the Aufess catchment area, medieval sedimentation rates are reported to be much higher than those for the entire 5.1 to 1 ka BP period, but are not separately quantified by Fuchs et al. (2011). Colluvial sediment deposition in the Valdaine region is high in comparison to other catchment areas, and attains values that in other catchment areas are only reached during a sedimentation peak in the last 1000 years (see table 2). From these data, it is clear that colluvial deposition in the Valdaine during the Roman period (1-500 AD) reached levels which in these other catchments were reached only when the landscape was for the first time fully dominated by humans, being much later than in the Valdaine.

| Region | Time Period | Catchment area specific colluvial deposition (ton $ha^{-1}$ $yr^{-1}$) | Source |
|---|---|---|---|
| Valdaine (France) | 700 -300 BC | Ca 1.5 | This study |
| | 250 - 50 BC | Ca -0.4 | This study |
| | 1BC/AD - 500 AD | Ca 2.6 to 3.4 | This study |
| | 500 AD – 900 AD | Ca 1.1 | This study |
| Dijle (Belgium) | 2000 BC – 1000 AD | 0.5 | (Notebaert et al., 2011a) |
| | 1000-2000 AD | 2.7 | (Notebaert et al., 2011a) |

| | | | |
|---|---|---|---|
| Geul (Belgium – Netherlands) | 1000-2000 AD | 5.7 | (de Moor and Verstraeten, 2008) |
| Rockenberg (Germany) | Last 5000 years | Ca 1.2 | (Houben, 2012) |
| Aufsess (Germany) | Last 5100 years | Ca 0.7 | (Fuchs et al., 2011) |

**Table 2: colluvial deposition as specific values (ton ha$^{-1}$ yr$^{-1}$) for selected catchment areas with a time-integrated sediment budget: the Valdaine (this study), Dijle (Notebaert et al., 2011a), Geul (de Moor and Verstraeten, 2008), Rockenberg (Houben, 2012) and Aufsess (Fuchs et al., 2011) catchment areas. Values for the Geul catchment area are based on modeling.**

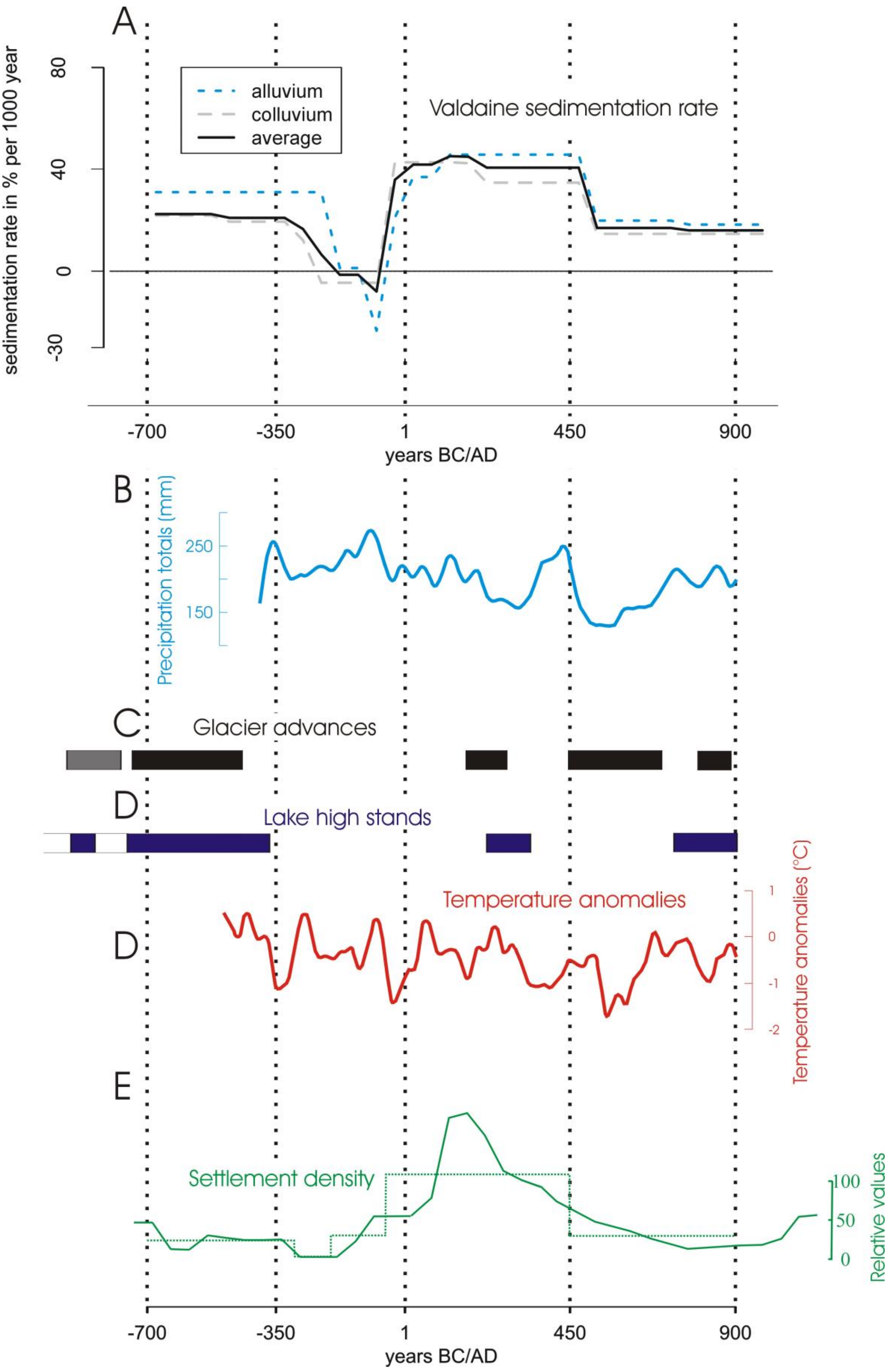

A
alluvium
colluvium
average
Valdaine sedimentation rate
sedimentation rate in % per 1000 year
80
40
0
-30
-700
-350
1
450
900
years BC/AD
B
Precipitation totals (mm)
250
150
C
Glacier advances
D
Lake high stands
D
Temperature anomalies
Temperature anomalies (°C)
1
0
-1
-2
E
Settlement density
100
50
0
Relative values
-700
-350
1
450
900
years BC/AD

**Fig. 5: Comparison of the sedimentation rates (SRr) with environmental variables. A) average sedimentation rates for the Valdaine catchment area (fig. 3B); B) precipitation totals (mm) for central Europe (Buntgen et al., 2011); C) Swiss glacier advances (Holzhauser et al., 2005; Joerin et al., 2008) D) high lake stands in the French Alps and northern Jura (Magny, 2004); E) temperature anomalies (°C) for central Europe (Buntgen et al., 2011); F) relative settlement density in the Valdaine and nearby Tricastin (based on Berger (1996) and complemented with new data by Berger (2015)); the dashed line represents average values for some periods that are based on the major cultural phases.**

Comparison of the sediment budget with data on settlement density indicates the important influence of settlement density and associated land use on soil erosion and sediment deposition over a timescale of 200 to 500 years (fig. 5). Periods of increased anthropogenic pressure, and notably the Roman period as a whole, are responsible for increased soil erosion and sediment deposition. Also, a decrease in anthropogenic pressure results in a decrease in soil erosion, with stability for many of the studied colluvial sites, and incision for others (Berger, 2003). This incision can be explained by a 'clear water effect', which means that water discharge that is relatively depleted in sediment (because of decreased erosion rates) is compensated by fluvial incision.

When variations on a more detailed timescale (50-100 years) are considered, the relation between sedimentation rates and settlement density is less prominent. This can, at least partially, be explained by the lack of detail in the original time resolution of sediment deposition selected for quantification (see above). A more precise time frame is recorded on a regional scale (Berger, 2003; Berger et al., 2007a; Salvador and Berger, 2014), but these data are not quantifiable at such a resolution. As a result, the variation in the settlement density which can be observed within, for example, the Roman period (50 BC – 400 AD) can only be partially observed in the sedimentation rates. The maximum peak in Roman settlement density appears to fall after the increase in sediment deposition (fig. 5), but this is merely the result of the temporal precision. On a regional scale, there is an important increase in settlements and in settlement size during the first century AD (Berger, 2015), coinciding with the peak in SR.

The detailed climatic data provided by Buntgen et al. (2011), which are established for a region starting ca. 350 km northeast of the Valdaine, show major variations for the considered time period (700 BC – 900 AD), typically with a length of less than 200 years (fig. 5). Also the variations in lake records (Magny, 2004) and glacial advances (Holzhauser et al., 2005; Joerin et al., 2008) show variations on timescales of a few centuries at most (fig. 5). Variations, especially in precipitation, may be different for the Valdaine, as it is vulnerable to variations at the northern limit of Mediterranean rains (Berger, 1996). There is also a possible relationship between cultural periods (and land use intensity) and climate (Buntgen et al., 2011). Periods with increased precipitation, or increased variability in precipitation, are not individually recognizable in the sedimentary record, and the same is true for dry periods (see also Berger (1996)). This is possibly the consequence of the sediment budget that fails to show variations at a timescale more detailed than 200-500 years, but also partly by the continuous effects of anthropogenic forcing on soil cover and stability, which amplifies the runoff process. The effects of a higher frequency of extreme rain events during warm periods such as the Roman Warm Period is also being discussed for the regional scale (Giguet-Covex et al., 2012; Arnaud et al., 2012). The geomorphic impact of such events in term of sedimentary budget is difficult to evaluate in fluvial and colluvial archives.

## VI. CONCLUSIONS

In this study an overview of alluvial and colluvial deposition in the Valdaine region between 700 BC and 900 AD is given, the period with the first widespread anthropogenic dominance of the landscape. Detailed descriptions of sediments for three sites are presented, and together with a database of published and unpublished profiles from cores and trenches they are used to construct a sediment budget that quantifies the different sediment sinks in a temporal framework. The main results are:

- The temporal evolution of sediment deposition, stability and incision is reconstructed for the period 700 BC-900 AD. The major changes in geomorphic processes and sediment dynamics in the catchment area could be identified within a temporal resolution of ca. 50 years. But variations within the major deposition periods that are separated by such major changes could not be identified, and sediment deposition (or incision) is thus averaged out over 200-500 years.
- Variation in sedimentation in colluvial and alluvial sinks shows a clear relationship with land use history on a timescale of 200-500 years, while the major periods of geomorphic change that are more precisely dated coincide with changes in the land use history as well. The results show how more intense land use leads to increased deposition rates, while decrease in land use leads to stability or even a clear-water effect with incision.
- The major peak in sedimentation occurred during the Roman period ca. 100/50 BC-450 AD, a period of unprecedented human land use, which coincides with intensification of soil cultivation, anthropogenic management of the water network and market economy growth on a continental scale. Roman deposition rates are comparable to deposition rates during intense occupation phases which have taken place in the last 1000 years in catchment areas of Central and Western Europe. This is clear evidence for a generalized anthropogenic forcing on the landscape that occurred from the Iron Age to the end of the Roman period (100 BC-450 AD), with an immense rise in the sediment deposition (7 to 16 times) in comparison with the Neolithic/Bronze Age period (Notebaert et al., 2014).

- We found no influence of typically short-phased climatic fluctuations (pluri-decadal) in the sedimentation record. This is possibly due to the limited temporal resolution of our sediment archive.

The sediment budget presented provides a clear example of the overwhelming impact of human land use on the sedimentary system. The Valdain basin appears to be a system already conditioned by a long history of human impact, quantifiable beginning with the First Iron Age. This quantified budget of long and intensive soil exploitation enables us to identify the Roman impact on northern Mediterranean landscapes as an anomaly, and to question its real effects on populations. Plato (IVth c. BC) and the Roman agronomist Columella (Ist c. AD) were conscious of the effects of deforestation and soil erosion during the Greek and Roman periods. We can hypothesise the potential links between Mediterranean environmental change, the geomorphic effect of which is measurable today, unsustainable policies and the market economy practices of local actors close to those of today, and the regular agrarian crises that we observe in the historical and archaeological archives (Butzer, 2011; Dearing, 2006; van der Leeuw and Team, 2005). Without reference to collapse theory, these geomorphic processes modified everyday conditions for the populations (through soil depletion, repeated degradation of hydraulic systems, the effect of and on structures such as bridges and roads through changes in water and sediment discharge...), thus affecting agrarian production. These new results must be integrated into socio-environmental hypotheses concerning ancient societies as well as climatic, volcanic, socio-political, and military mechanisms. Quantitative measurements of sediment budgets at a regional scale that have been carried out in the last few years are comparable to what has been achieved in climate-change studies. They represent a new opportunity to distinguish natural from anthropogenic factors in the evolution of landscapes, and to better characterize the advent of the Anthropocene in terrestrial environments. However, chronostratigraphical contexts require further improvements in order to better discriminate between human influences and short termed climatic events.

## References


Arnaud F, Révillon S, Debret M, et al. (2012) Lake Bourget regional erosion patterns reconstruction reveals Holocene NW European Alps soil evolution and paleohydrology. *Quaternary Science Reviews* 51: 81-92.

Berger J-F. (1996) Le cadre paléogéographique des occupations du bassin valdainais (Drôme) à l'Holocène. . Paris, France: Université Paris I, 325.

Berger J-F. (2003) Les étapes de la morphogenèse holocène dans le sud de la France. In: CNRS (ed) *Archéologie et systèmes socio-environnementaux. Études multiscalaires sur la vallée du Rhône dans le programme Archaeomedes.* Paris: CNRS, 87-167.

Berger J-F. (2011) Hydrological and post-depositional impacts on the distribution of Holocene archaeological sites: The case of the Holocene middle Rhône River basin, France. *Geomorphology* 129: 167-182.

Berger J-F. (2015) Approche socio-environnementale du Néolithique à l'Anthropocène : quelques études intégrées de la vallée du Rhône aux milieux arides (Arabie, Asie centrale). Université Lyon 2-Lumière.

Berger J-F and Brochier J-L. (2006) Les apports de la géoarchéologie à la connaissance des paysages et des climats de l'époque médiévale en moyenne vallée du Rhône. In: Maufras O (ed) *Habitats, nécropoles et paysages dans la moyenne et basse vallée du Rhône (VIIe–XVe s.): conributions des travaux archéologiques sur le tracé du TGV Méditerranée à l'étude des sociétés rurales médiévales, Documents d'Archéologie française.* Paris: Éditions de la maison des Sciences de l'Homme, 163-208.

Berger J-F, Brochier J-L, Vital J, et al. (2007a) Nouveau regard sur la dynamique des paysages et l'occupation humaine à l'âge du Bronze en moyenne vallée du Rhône. In: Richard H and Mordant C (eds) *Le Temps, Actes du 109e congrès des CTHS. Emprises, déprises et rythmes agricoles à l'Âge du Bronze.* Besançon: Éditions du CTHS, 260-283.

Berger J-F, Fiches J-L and Gazenbeek M. (2003) Origin of fluvial fluctuations of the River Vidourle and their effect on the organisation and evolution of the site of Ambrussum (Hérault, France) between the Iron Age and late Antiquity. In: Fouache E (ed) *International Conference, The Mediterranean World Environment and History.* Université Paris-1, Panthéon-Sorbonne, 77-108.

Berger J-F and Guilaine J. (2009) The 8200calBP abrupt environmental change and the Neolithic transition: A Mediterranean perspective. *Quaternary International* 200: 31-49.

Berger J-F and Jung C. (1999) Rapport fossés: fossés et voirie. Operation transversalle. AFAN-TGV Ligne 5 Secteur II: Valance-Avignon. *Archéologie et TGV: rapport de fouille.* Bron, France: AFAN TGV.

Berger J-F, Magnin F, Thiébault S, et al. (2000) Emprise et déprise culturelle à l'Age du Bronze: l'exemple du Bassin Valdainais (Drôme) et de la moyenne vallée du Rhône. *Bulletin de la Société préhistorique française* 97: 95-119.

Berger J-F, Nuninger L and Van der Leeuw SE. (2007b) Modeling the Role of Resilience in Socio-Environmental Co-Evolution: the Middle Rhone Valley between 1000 BC and ad 1000. In: Kolher T and Van der Leeuw SE (eds) *Modeling Socioecological Systems.* Santa-Fé: Sarre editions, 41-59.

Blanchet G. (1990) Régimes météorologiques et diversité climatique dans l'espace rhonalpin / Meteorological regimes and climatic diversity in the Rhône-Alpes area. *Revue de géographie de Lyon*: 106-117.

Brochier JL and Berger JF. (in prep.) Des paysages et du climat de la fin des temps glaciaires à nos jours en moyenne vallée du Rhône d'après les données des travaux archéologiques du TGV Méditerranée.

Buntgen U, Tegel W, Nicolussi K, et al. (2011) 2500 years of European climate variability and human susceptibility. *Science* 331: 578-582.

Butzer KW. (2011) Geoarchaeology, climate change, sustainability: A Mediterranean perspective. *Geological Society of America Special Papers* 476: 1-14.

de Moor JJW and Verstraeten G. (2008) Alluvial and colluvial sediment storage in the Geul River catchment (The Netherlands) — Combining field and modelling data to construct a Late Holocene sediment budget. *Geomorphology* 95: 487-503.

Dearing JA. (2006) Climate-human-environment interactions: resolving our past. *Climate of the Past* 2: 187-203.

Delhon C and Thiebault S. (2008) An approach to Holocene vegetation history in the middle Rhone valley (France): anthracological data from the «TGV-Méditerranée» excavations. *Charcoal from the past, Cultural and palaeoenvironmental implications. Proceedings of the Third International Meeting of Anthracology, Cavallino– Lecce (Italy), June 28th– July 1st 2004.* Archaeopress, 63-73.

Dotterweich M. (2008) The history of soil erosion and fluvial deposits in small catchments of central Europe: Deciphering the long-term interaction between humans and the environment — A review. *Geomorphology* 101: 192-208.

Doyen É, Vannière B, Berger J-F, et al. (2013) Land-use changes and environmental dynamics in the upper Rhone valley since Neolithic times inferred from sediments in Lac Moras. *The Holocene* 23: 961-973.

Dusar B, Verstraeten G, Notebaert B, et al. (2011) Holocene environmental change and its impact on sediment dynamics in the Eastern Mediterranean. *Earth-Science Reviews* 108: 137-157.

Fuchs M, Will M, Kunert E, et al. (2011) The temporal and spatial quantification of Holocene sediment dynamics in a meso-scale catchment in northern Bavaria, Germany. *Holocene* 21: 1093-1104.

Giguet-Covex C, Arnaud F, Enters D, et al. (2012) Frequency and intensity of high-altitude floods over the last 3.5 ka in northwestern French Alps (Lake Anterne). *Quaternary Research* 77: 12-22.

Hirsch F and Vincent M. (1966) Aspects climatiques du bassin du Jabron (Drôme). *Revue de géographie alpine* 54: 457-467.

Hoffmann T, Erkens G, Cohen KM, et al. (2007) Holocene floodplain sediment storage and hillslope erosion within the Rhine catchment. *Holocene* 17: 105-118.

Holzhauser H, Magny M and Zumbuühl HJ. (2005) Glacier and lake-level variations in west-central Europe over the last 3500 years. *The Holocene* 15: 789-801.

Houben P. (2012) Sediment budget for five millennia of tillage in the Rockenberg catchment (Wetterau loess basin, Germany). *Quaternary Science Reviews* 52: 12-23.

Joerin U, Nicolussi K, Fischer A, et al. (2008) Holocene optimum events inferred from subglacial sediments at Tschierva Glacier, Eastern Swiss Alps. *Quaternary Science Reviews* 27: 337-350.

Lane EW. (1955) Design of stable channels. *Transactions of the American Society of Civil Engineers* 120: 1234-1260.

Magny M. (2004) Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. *Quaternary International* 113: 65-79.
Notebaert B, Berger J-F and Brochier JL. (2014) Characterization and quantification of Holocene colluvial and alluvial sediments in the Valdaine Region (southern France). *The Holocene* 24: 1320-1335.
Notebaert B and Verstraeten G. (2010) Sensitivity of West and Central European river systems to environmental changes during the Holocene A review. *Earth-Science Reviews* 103: 163-182.
Notebaert B, Verstraeten G, Govers G, et al. (2010) Quantification of alluvial sediment storage in contrasting environments: Methodology and error estimation. *Catena* 82: 169-182.
Notebaert B, Verstraeten G, Rommens T, et al. (2009) Establishing a Holocene sediment budget for the river Dijle. *Catena* 77: 150-163.
Notebaert B, Verstraeten G, Vandenberghe D, et al. (2011a) Changing hillslope and fluvial Holocene sediment dynamics in a Belgian loess catchment. *Journal of Quaternary Science* 26: 44-58.
Notebaert B, Verstraeten G, Ward P, et al. (2011b) Modeling the sensitivity of sediment and water runoff dynamics to Holocene climate and land use changes at the catchment scale. *Geomorphology* 126: 18-31.
Reid LM and Dunne T. (2005) Sediment budgets as an organizing framework in fluvial geomorphology. In: Kondolf GM and Piégay H (eds) *Tools in Fluvial Geomorphology.* Chichester: John-Wiley & Sons Ltd, 463-500.
Ronco C, Brochier J-L, Ferber F, et al. (2008) Rapport de diagnostic avril 2008. Canalisation de transport de gaz. . Bron, France: INRAP.
Salvador P-G and Berger J-F. (2014) The evolution of the Rhone River in the Basses Terres basin during the Holocene (Alpine foothills, France). *Geomorphology* 204: 71-85.
Simonneau A, Doyen E, Chapron E, et al. (2013) Holocene land-use evolution and associated soil erosion in the French Prealps inferred from Lake Paladru sediments and archaeological evidences. *Journal of Archaeological Science* 40: 1636-1645.
Slaymaker O. (2003) The sediment budget as conceptual framework and management tool. *Hydrobiologia* 494: 71-82.
Stolz C, Grunert J and Fulling A. (2012) The formation of alluvial fans and young floodplain deposits in the Lieser catchment, Eifel Mountains, western German Uplands: A study of soil erosion budgeting. *Holocene* 22: 267-280.
Thiercelin-Ferber F. (2012) Route d'Espeluche Aménagement et extension du stade Beaulieu.: Inrap Rhône-Alpes / Auvergne.
Trimble SW. (1999) Decreased rates of alluvial sediment storage in the coon creek basin, wisconsin, 1975-93. *Science* 285: 1244-1246.
Trimble SW. (2009) Fluvial processes, morphology and sediment budgets in the Coon Creek Basin, WI, USA, 1975–1993. *Geomorphology* 108: 8-23.
Trimble SW. (2010) Streams, valleys and floodplains in the sediment cascade. In: Burt TP and Allison RJ (eds) *Sediment Cascades: An Integrated Approach.* John Wiley & Sons, Ltd, 307-343.
van der Leeuw SE, Favory F, Fiches J-L, et al. (2003) *Archéologie et systèmes socio-environnementaux: études multiscalaires sur la vallée du Rhône dans le programme Archaeomedes*: CNRS.
van der Leeuw SE and Team AR. (2005) Climate, hydrology, land use, and environmental degradation in the lower Rhone Valley during the Roman period. *Comptes Rendus Geoscience* 337: 9-27.
Verhagen P and Berger J-F. (2007) The hidden reserve. Predictive modelling of buried archaeological sites in the Tricastin-Valdaine region (Middle Rhône Valley, France). *Case Studies in Archaeological Predictive Modeling* 14: 41.
Verstraeten G, Lang A and Houben P. (2009a) Human impact on sediment dynamics—quantification and timing. *Catena* 77: 77-80.
Verstraeten G, Rommens T, Peeters I, et al. (2009b) A temporarily changing Holocene sediment budget for a loess-covered catchment (central Belgium). *Geomorphology* 108: 24-34.

Vital J, Brochier J-L, Durand J, et al. (1999) Roynac le Serre 1 (Drôme): une nouvelle séquence holocène en Valdaine et ses occupations des Âges des métaux. *Bulletin de la Société préhistorique française* 96: 225-240.